DSP-Based EIS Instrumentation
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ABSTRACT:
Electrochemical Impedance Spectroscopy (EIS) remains the primary method to assess the corrosion of metals, including the degradation of protective coatings. As such, effective EIS instrumentation remains a fundamental need. The primary focus of this project is the design and implementation of a prototype EIS instrument that incorporates a variety of features that improve performance compared with traditional EIS systems.

This report summarizes the accomplishments completed during the past year by the Electrical and Computer Engineering (ECE) group at North Dakota State University (NDSU). Activities are classified in four general categories: 1) completion of a prototype EIS instrument, 2) assessment of prototype performance and limitations, 3) development and refinement of various EIS methods and features, and 4) initial design and development of a new EIS prototype. Activities and accomplishments are detailed in the four correspondingly-numbered sections of this report. A final section, Section 5, provides conclusions as well as future directions.

1. COMPLETION OF A PROTOTYPE EIS INSTRUMENT
In the original statement of work for this project, the primary project goal is the design, construction, and testing of a prototype device capable of performing EIS measurements using various advancements in EIS theory. In December 2004, a prototype device was delivered and demonstrated to the Department of Coatings and Polymeric Materials (CPM) at NDSU. Figure 1 shows the packaged custom components of the system while Figure 2 shows these custom components, in an unpackaged state, connected to a typical corrosion cell.

Figure 1: DSP-Based EIS Prototype with Final Packaging

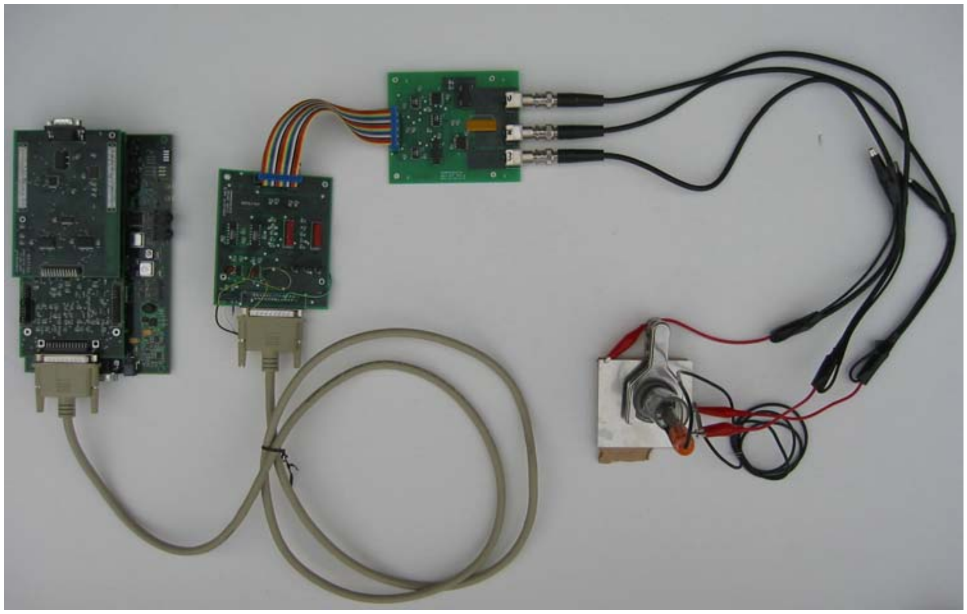

Figure 2: Unpackaged DSP-Based EIS Prototype Connected to Corrosion Cell

The completed prototype includes three basic components: 1) a host Personal Computer (PC) for parameter selection and data collection, 2) a Digital Signal Processing (DSP) unit for operation control and task management, signal generation, signal sampling, and impedance estimation, and 3) an analog interface unit that adheres with standard potentiostatic or galvanostatic operations. Figure 3 (a) provides a block diagram of the system, organized so that each of the primary blocks is easily identified, and Figure 3 (b) shows the typical cell configuration needed to conduct an experiment.

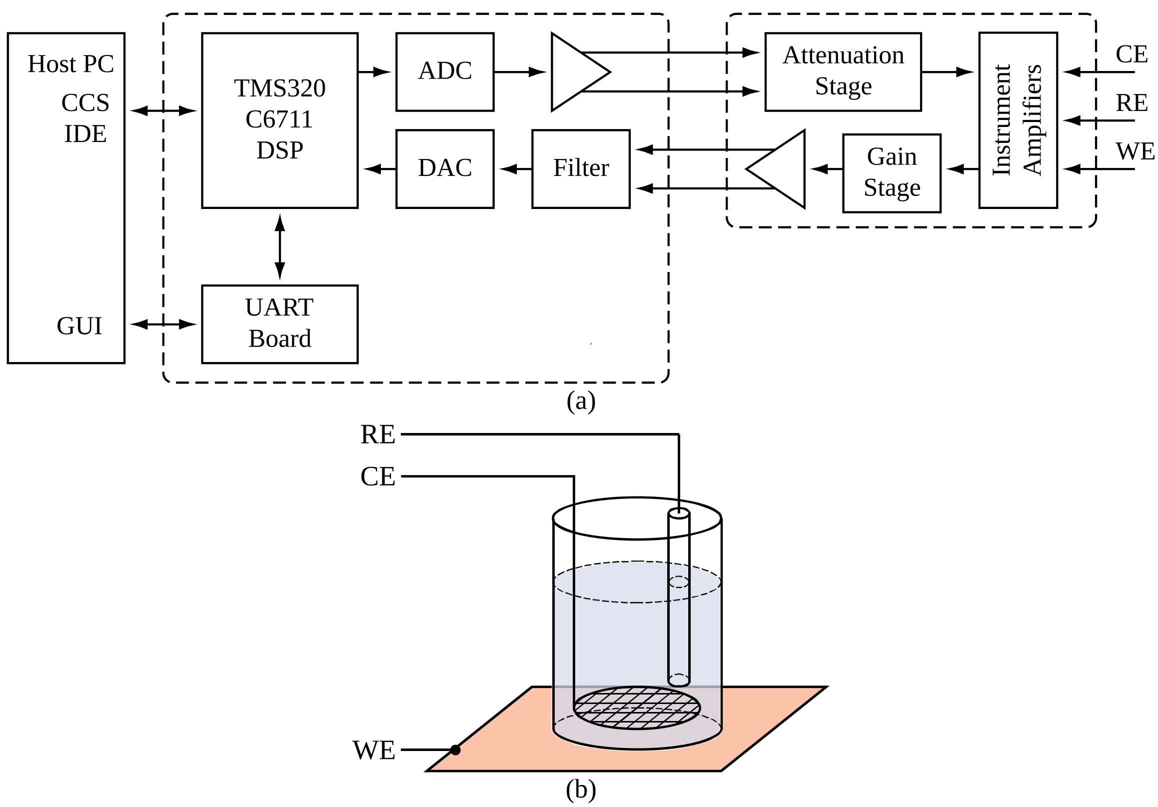

Figure 3: (a) EIS System Block Diagram and (b) Typical Cell Configuration

Host PC Component
To begin an experiment, the EIS application code is downloaded to the target DSP using the Code Composer Studio (CCS) tool provided by the DSP manufacturer, Texas Instruments. Next, the custom GUI, written using MATLAB, is launched, which provides the user with a convenient interface to control the device, set parameters, and collect, display, and save the resultant data. Figure 4 shows a screen shot of the final version of the GUI, which is significantly modified from the original. New features include increased system configurability as well as improved parameter and task monitors.

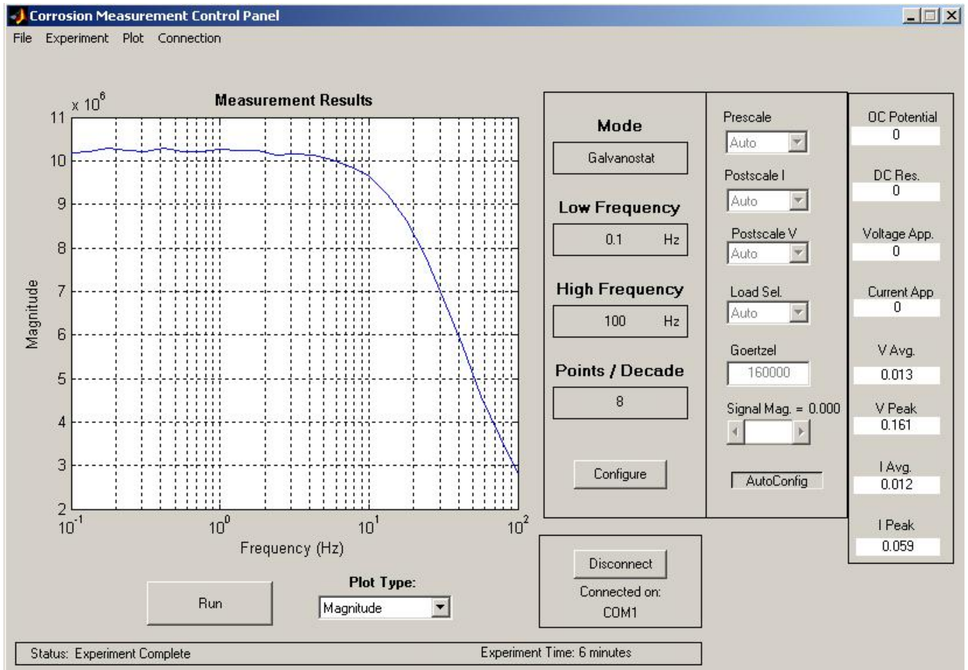

Figure 4: GUI Screen-Shot

DSP Component
The DSP software involves 1) a calibration mode, 2) design of a low peak-factor pseudo-logarithmically spaced multi-frequency test signal, 3) signal generation and application to the target cell, 4) sampling of return waveforms, and 5) computation of complex impedance as a function of frequency. Additionally, custom DSP daughter boards provide data converters, signal drivers, filters, and supplemental communication ports necessary to interface the DSP to the analog interface board as well as the host PC.

The EIS application code on the DSP implements a range of features not typically found on commercial EIS equipment. First, the test signal is composed of a superposition of multiple frequencies, each component individually generated using recursive digital oscillators, that are simultaneously applied to the target cell. The relative phases of these components are adjusted to ensure the resulting multi-tone signal has a low peak factor, which is desirable as it allows increased signal power while maintaining an overall peak amplitude that is still within the target cell's range of approximately linear operation. This phase estimation, which is a non-linear problem, is accomplished during run-time using a gradient-descent-based approach. The component sinusoids are chosen using a pseudo-logarithmic frequency spacing that allows the resultant multi-tone signal to still be periodic. Periodicity is necessary to ensure meaningful phase optimization as well as accurate frequency analysis. The pseudo-logarithmically spaced tones also justify an alternate method of frequency analysis during the impedance calculations. Rather than the typical Fast Fourier Transform (FFT) based approach, parallel Goertzel algorithms are implemented, one for each frequency component. In this case, the Goertzel approach significantly reduces memory requirements and all but eliminates estimate latencies typical of FFT implementations.

When utilizing frequencies in the milli-hertz range, experiment execution times are significant. Once the experiment is started, the prototype system, unlike most commercial systems, can be disconnected from and reconnected to the host PC without disrupting the experiment. Although desirable from the simple standpoint of freed computer resources, it also represents the first step necessary to achieving a fully portable in-situ EIS-based health monitor.

Analog Interface Component

The analog interface boards are designed to support both galvanostatic and potentiostatic operation. However, due to time and resource constraints, the final DSP code only supports galvanostatic operation. The functional circuit diagram of the analog interface board closely follows a previous design [1,2]. However, updated components, such as newly available extremely low bias-current operational amplifiers, are utilized to help improve system performance. New board layouts are utilized, including differential signal driving to reduce noise effects. The analog interface boards are placed within the faraday cage that holds the experiment, separate from digital circuitry of the DSP board which is outside the cage.

Additional implementation details for all system components can be found in the previous annual report.

2. ASSESSMENT OF PROTOTYPE PERFORMANCE AND LIMITATIONS

Many tens of experiments were conducted to test system performance. All tests were conducted using galvanostat mode using a variety target cells and frequency ranges. For practicality, only a representative selection of results is presented. Many of the results given in this section, as well as the following section, were presented in [3].

Initial testing concentrated on using simple passive elements. Figure 5 illustrates two such tests. The first utilized a single 10.19 mega-Ohm resistor. The second test added a 0.0091 micro-Farad capacitor in parallel to the 10.19 mega-Ohm resistor. Both tests, with measured data points marked in blue, are reasonably consistent with the theoretical results, shown as solid black lines. As shown, purely resistive loads were typically not as accurate as loads with some capacitance. Fortunately, most corrosion cells have at least some capacitive element. Still, additional investigation needs to be performed as to why the system has difficulty in these cases.

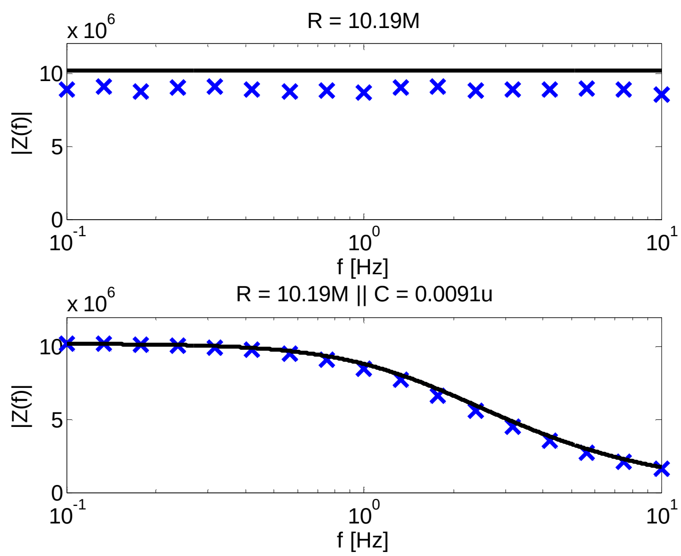

Figure 5: Magnitude Impedance for (a) Simple Resistor and (b) Resistor and Capacitor in Parallel

Figure 6 shows typical results obtained with a standard Randle's circuit. In these plots, data from the prototype DSP-based EIS instrument is shown in blue and data from a commercial Gamry EIS system, operating in potentiostat mode, are shown in red. Attempts to operate the Gamry device in galvanostat mode did not provide meaningful data. It is worth noting that the prototype device tests all frequencies

simultaneously while the Gamry device tests frequency points sequentially, and the estimation methods and exit criteria are different for each device as well. This makes comparison of many aspects of the two devices difficult. Still, general comparisons can be made. The magnitude impedance plots, shown in Figure 6 (a), are good for both devices and consistent with the theoretical response. Figure 6 (b) shows the error of the two measurements from the theoretical; it is interesting to note from this plot that both systems identify features not explained by the simple Randle's circuit model. The error is roughly the same order for both the prototype and commercial Gamry devices, although the Gamry device provides a somewhat smoother response. Notice also that the prototype device measured the circuit down to 1 milli-hertz, which resulted in rather long trial times.

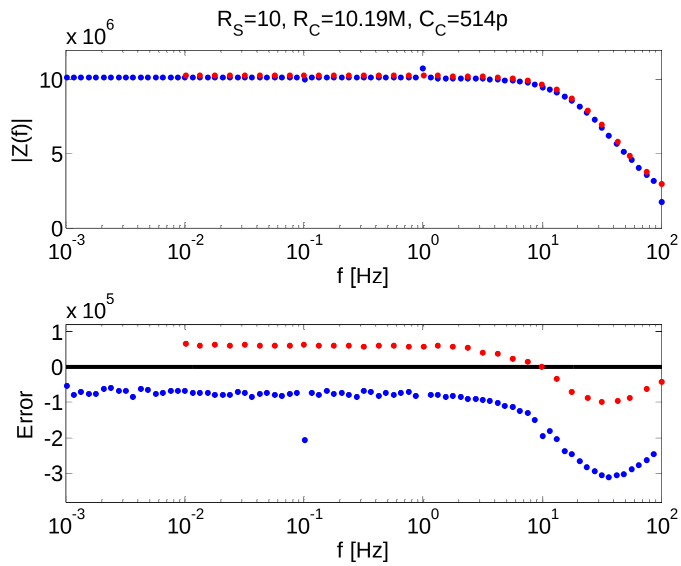

Figure 6: Randle's Circuit (a) Magnitude Impedance and (b) Error

Figure 7 illustrates results obtained using bare aluminum. The trials shown in blue are from the prototype DSP-based EIS system, while the trial shown in red corresponds to data collected from a Gamry device, configured similar to the cases presented in Figure 6. Overall, the trials are relatively consistent with one another. It is important to note that, by a matter of necessity, the aluminum target utilized is tested sequentially, with the Gamry device operating last, and that the dilute Harrison's solution used for the cell can impact the properties of the aluminum over time. It is also worth pointing out that the data from the commercial Gamry device has clear difficulty with the sample at low frequencies. This emphasizes the general difficulty in constructing instrumentation that is capable of successfully operating on all possible targets.

Figure 8 shows the results of both the prototype EIS system, in blue, and the Gamry EIS system, in red, for an epoxy-coated aluminum sample. In this case the Gamry device provides a result that is consistent with theoretical expectations, while the prototype device provides completely unsatisfactory results. This trial was completed after the students primarily responsible for the system implementation had left the project. As a result of these students' premature departures, system debugging and modification have been extremely difficult. This difficulty is exacerbated by the complexity of the system design. Inclusion of the custom GUI, for example, added about a year to the system development time, increased hardware complexity significantly due to communications requirements, and contributed to bloating the DSP code by a significant amount. The attempt to support both potentiostatic and galvanostatic operations delayed system development, increased hardware complexity, and again bloated code. In the end, neither of these two requested features assisted in demonstrating algorithm advancements. Actually, these features are counterproductive or undesirable towards a newly identified objective of designing devices appropriate for portable or in-situ health monitor applications. To facilitate more rapid development and improved debugging, the new EIS-prototype under development and outlined in Section 4 is significantly scaled back, although with little or no expected loss in capability or configurability.

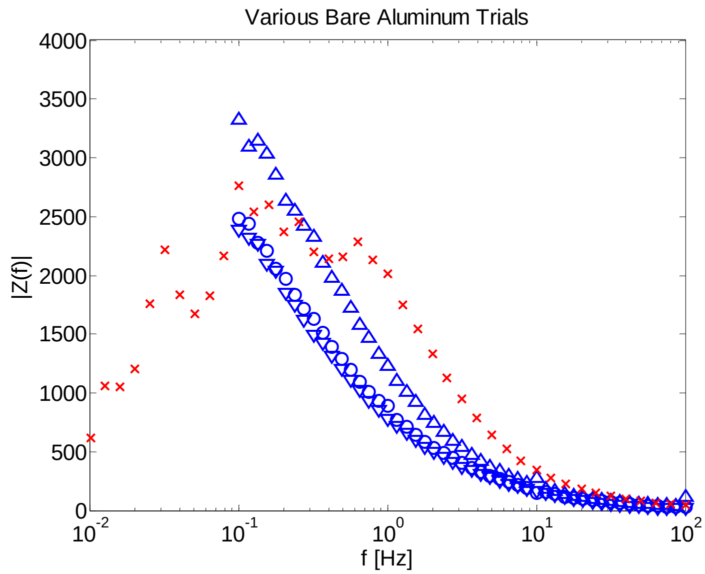

Figure 7: Bare Aluminum Magnitude Impedance

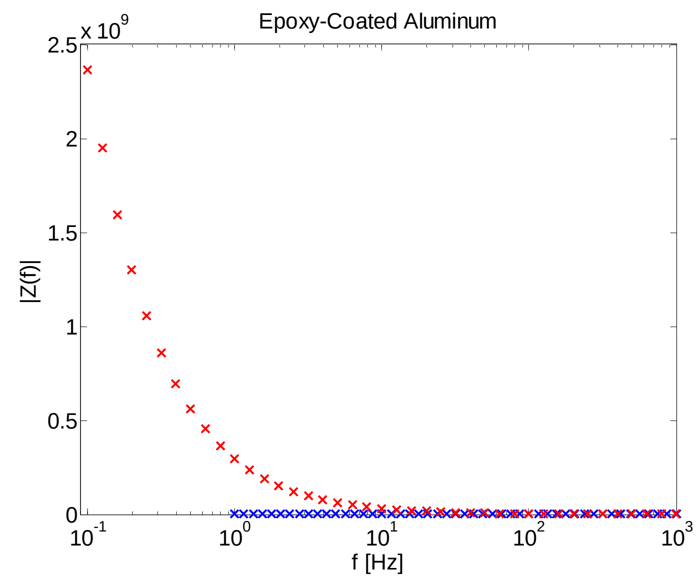

Figure 8: Coated Aluminum Magnitude Impedance

3. DEVELOPMENT AND REFINEMENT OF VARIOUS EIS METHODS AND FEATURES
An earlier DSP-based EIS instrument, described in [1,2], utilized a multi-tone test signal with linearly spaced frequencies. Unfortunately, most corrosion studies are interested in wide frequency ranges, and data is typically plotted using a logarithmic frequency scale. Linearly spaced frequency components are not well suited to such applications, and may even contribute to reduced system performance, since signal power is over-represented in some regions and underrepresented in others.

Figure 9 (a) shows 100 linearly-spaced frequency measurements for an *RC* circuit similar to the case presented in Figure 5. What is immediately apparent is that high frequencies are over-represented while low frequencies are only sparsely represented. Using blue markers, Figure 9 (b) shows 25 logarithmically spaced measurements for the same circuit. Although only a quarter as many terms are used, the logarithmic spacing yields five or six times better resolution at low frequencies and does not over-represent the high frequencies.

The problem with a true logarithmic spacing, however, is that the resulting multi-tone test signal cannot be periodic. Without periodicity, there is no way to reduce the signal's peak factor. Furthermore, practical frequency analysis conducted on a non-periodic signal always results in frequency smearing and leakage, which thereby degrades the resulting estimates of impedance. Periodicity is required for a practical well-designed system. By rounding the location of each logarithmic component to an integer multiple of some base frequency, however, a pseudo-logarithmically spaced multi-tone signal can be constructed that is periodic (with period given by the reciprocal of the base frequency). Rounding the blue markers in Figure 9 (b) to two decimal places, for example, results in signal with a period of 100 seconds. For the prototype described in Section 1, the multi-tone signals were all constructed in this manner, with the resulting period being 100 times the period of the lowest frequency.

Upon further investigation, however, it turns out that using a somewhat arbitrary factor like 100 is not necessarily desirable. The red markers in Figure 9 (b), for example, show the component locations when rounded to the nearest 1/6 of a hertz. The resulting frequency locations are very nearly logarithmic (more so at high frequencies, less so at low frequencies), and the period of the resulting multi-tone signal is now only six. Reduced periods can facilitate more rapid and flexible analysis, as well as better treatment of the time-varying processes typical of corrosion cells

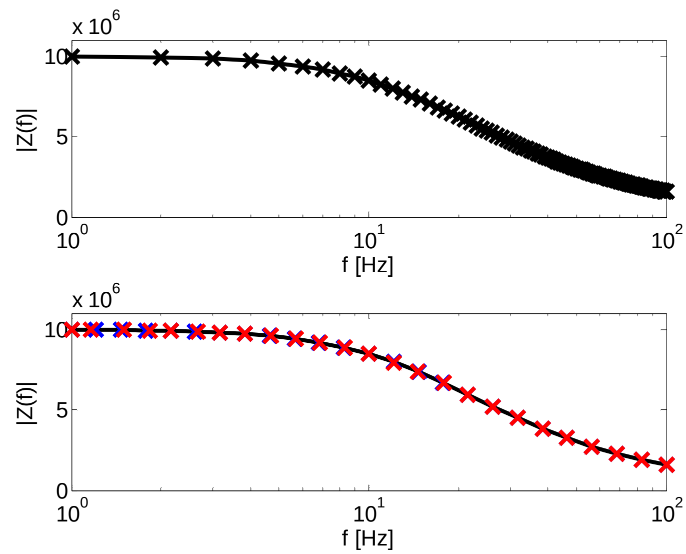

Figure 9: (a) Linearly Spaced Components and (b) Logarithmically Spaced Components

Many parameters (such as number of points per decade, number of decades, period) can impact the quality (component position, availability of harmonics) of the resultant multi-tone signal. Figure 10 provides some illustration of the complex nature of the problem for a test signal that spans two decades of frequency from 1 to 100 Hertz. First, a suitable number of points per decade (NPD) is chosen; most existing systems choose this number arbitrarily as 10, 20, or some other conveniently round number. However, such choices are not necessarily the best. Figure 10 shows the maximum relative position error among components over two decades as a function of signal period for four different, but similar, point densities. All cases show the expected general trend that maximum relative position error decreases as signal period increases. However, an arbitrary period selection of say 10 may or may not provide as accurate of placement as the more desirable and shorter period of 9, and this varies somewhat as a function of the number of points per decade. If too short of a period is attempted, multiple points are rounded to the same frequency point rendering the multi-tone signal unsuitable; this condition is indicated by red triangles. Typical corrosion cells are non-linear, and one way to monitor the system for undesirable non-linear effects is to ensure the first harmonic of each frequency component is unoccupied and then monitor these first harmonic bins. The blue triangles in Figure 10 identify cases where one or more first harmonics overlap with other frequency components of the multi-tone signal, which again renders the signal unsuitable. Clearly, the arbitrary

choice of 10 points per decade is not a good choice.   A much better choice is to use 12 points per decade, with a period of perhaps six, which is the case that was used in Figure 9 (b).

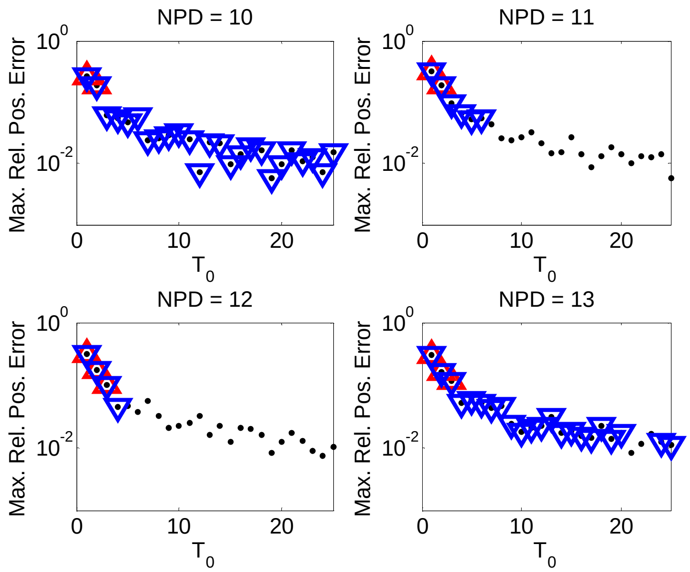

Figure 10: Influences of Parameter Choice on Resulting Test Signal

Once a suitable selection of pseudo-logarithmically spaced components is identified for the multi-tone test signal, it is important to optimize the relative phases to reduce the signal's peak factor. Consider the previous case of a signal that spans from 1 to 100 Hertz using 12 points per decade and a period of six. If all components have zero phase, the peak amplitude is 25, which is the worst case. Most existing multi-tone systems recognize this and therefore apply a random phase assignment. Using blue markers, Figure 11(a) illustrates the peak amplitude for a random-phase signal over 100 different trials. The red markers show the peak amplitude obtained using optimized phases found using a gradient-descent search algorithm, such as is used in the system described in Section 1.

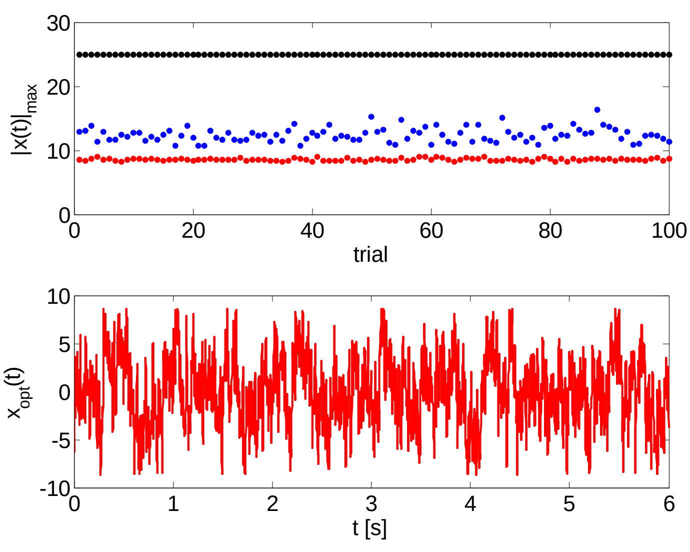

Figure 11: (a) Phase Strategies and (b) a Phase Optimized 25 Tone Signal

While random phases tend to improve (make smaller) the signal's peak amplitude, the optimized phases do a more consistent and better job and provide a better performance guarantee. In this particular case,

random phase assignment results in an average peak amplitude of 12.41 while the optimized phases result in an average peak amplitude of 8.54, which represents an overall reduction of over 30 percent. Figure 11(b) shows a sample phase-optimized signal for one of these trials; the signal, while noise-like in appearance, is highly controlled. Phase optimization can take place during run-time of the DSP-based system, or could be computed off-line and provided using look-up tables during system operation.

To summarize the most desirable properties, the constructed test signal should be a periodic signal composed of pseudo-logarithmically spaced sinusoids with phases optimized to reduce the overall peak factor of the signal. The period of the signal should be as small as possible while achieving the desired position accuracy, and at least the first harmonic of each term should be vacant to allow the system to monitor for nonlinear effects of the cell. The new system currently under development, and described in Section 4, will utilize a more optimized frequency placement strategy, consistent with these characteristics.

Preliminary work has also been conducted in two other areas. First, typical EIS systems require a wire connection between the processing unit and the experiment, which is typically contained in a faraday cage. This wire provides an electrical path that can allow noise, such as digital switching noise from the processing unit, to feed to the experiment. Investigation of an optical interconnect, among others, is now commencing. Such an optical interconnect would ensure the experiment is electrically isolated from the digital processing units, thereby reducing noise, and would also avoid the unpleasant task of routing wires through the faraday cage. Some interest has also been expressed from the department of polymers and coatings regarding wavelet analysis, for both ENM and EIS studies. Although some work has been conducted in the area (see [4] and [5]), apparently little attention has been paid to the selection of appropriate wavelet basis functions. Initial studies were conducted regarding potential basis-function selection criteria when using wavelet-based analysis methods. More work remains to be done in this area.

4. INITIAL DESIGN AND DEVELOPMENT OF A NEW EIS PROTOTYPE

While the prototype EIS system described in Section 1 satisfies its primary goals, it has certain deficiencies that limit the adaptation of the device to new project goals, such as development of fully portable and in-situ health monitors. As previously discussed, the custom GUI (including the associated hardware and embedded software) and the dual-mode analog front end (galvanostatic and potentiostatic operations) are not advantageous for such applications. As a result, a simplified prototype is currently under development.

By removing the GUI interface and dual-mode analog interface board, the new prototype is greatly simplified from the original, which will allow more rapid development, debugging, and testing. Such removals, however, completely change the entire system from hardware to software. Thus, significant system redesign is necessary. The new implementation is more compatible with the end goals of portable and in-situ health monitors. Previous GUI functionality can be accomplished through careful use of Texas Instrument’s (TI) Code Composer Studio (CCS) Integrated Development Environment (IDE). The new system will also upgrade the processor from a TI TMS320C6711, used in the prototype described in Section 1, to a newly released TI TMS320C6713 development board that offers USB support as well as improved board reliability.

Figure 12 shows the preliminary circuit schematic for a DSP daughtercard that provides data converters, signal drivers, and signal conditioning circuitry. Figure 13 shows the preliminary Galvanostat board, including signal drivers and variable gain circuitry. Both Figures reflect schematic layouts using the Mentor Graphics design suite of tools. The design in Figure 13 leverages from the original prototype’s analog interface board. Following a layout process, Printed Circuit Boards (PCBs) have been manufactured and populated. Board testing is now in progress.

New DSP code is also currently under development; code development will emphasize modularity so as to improve portability and algorithm development will incorporate recent advancements. Such code is necessarily complicated and reflects a significant design problem. Although still in the initial stages of code development, a fully operational system in anticipated within the upcoming year.

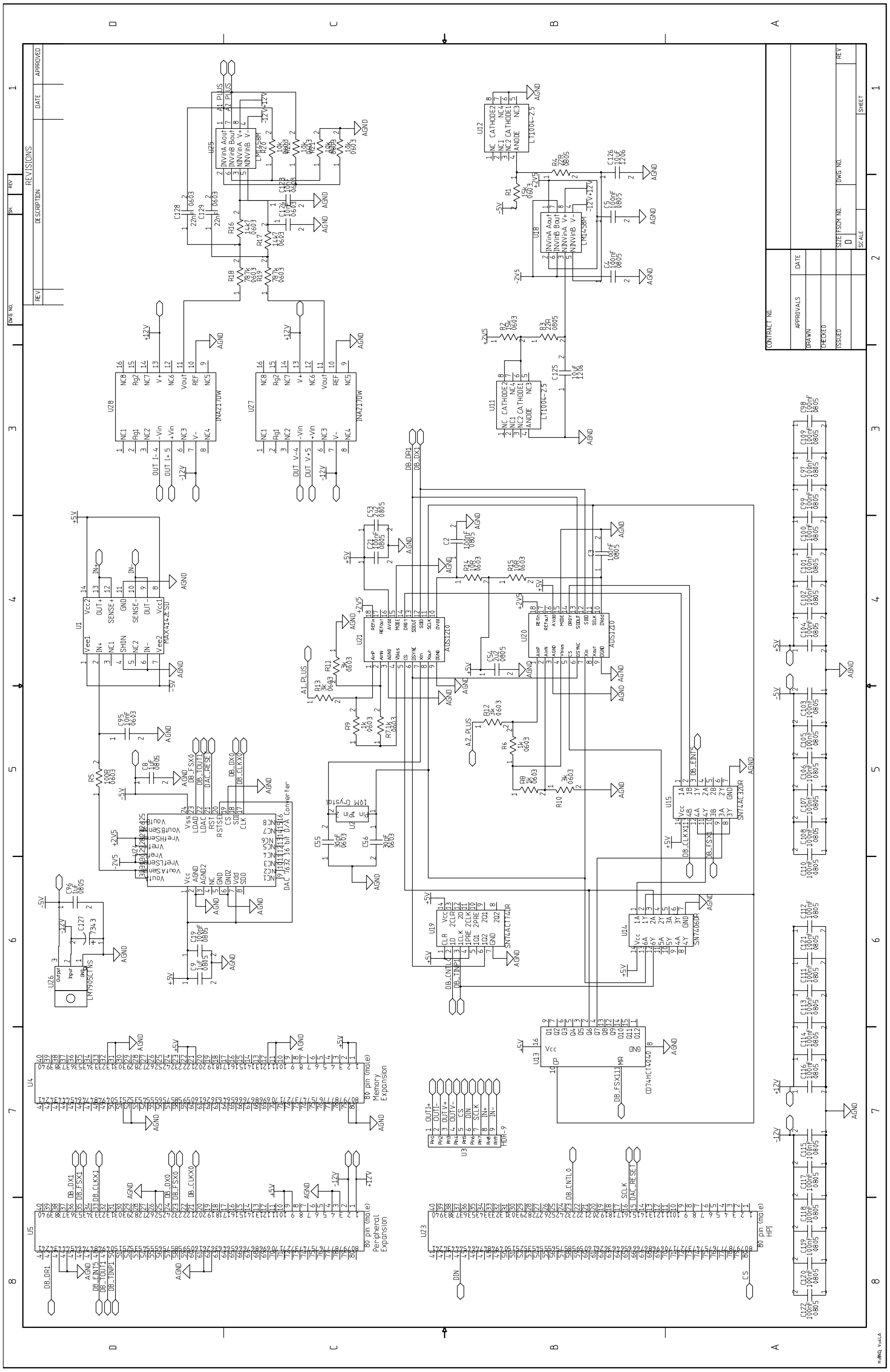

Figure 12: DSP Daughtercard for Data Converters, Drivers, and Signal Conditioning Circuitry

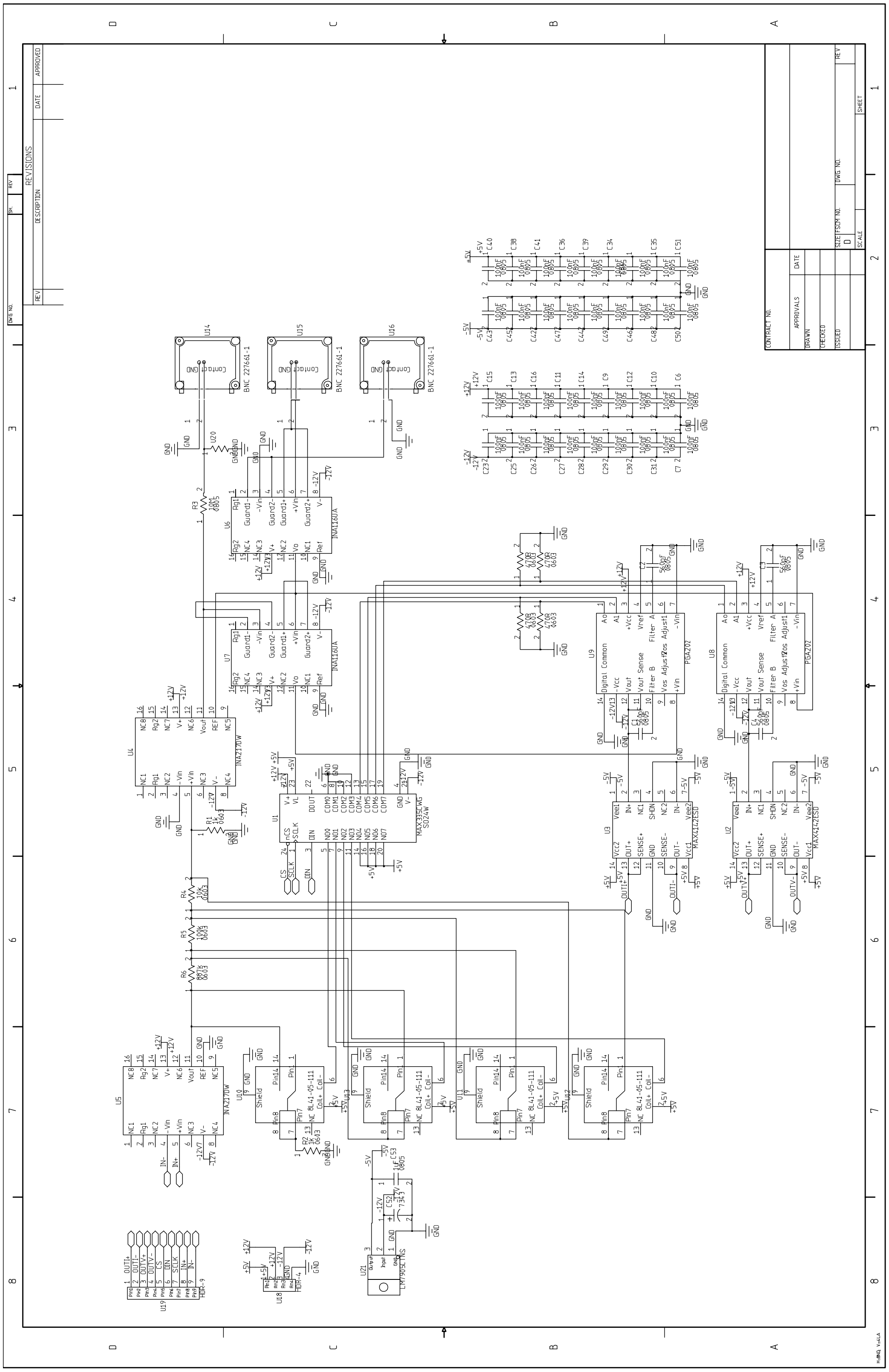

Figure 13: Galvanostat including Signal Drivers and Variable Gain Circuitry

5. CONCLUSIONS AND FUTURE DIRECTIONS

Activities during the first half of the past year have concentrated on the completion, delivery, and testing of the DSP-based EIS prototype. This implementation successfully demonstrates the use of a new low peak-factor pseudo-logarithmically spaced multi-frequency test signal. Additionally, the prototype utilized a variety of alternate processing algorithms, such as the Goertzel algorithm, that are better suited to this particular implementation. While the system provides comparable performance to commercial equipment in some cases, in others it does not. System complexity, while providing convenient features, also complicates system debugging, modification, and adaptation to new applications. As such, development has now begun on a simplified EIS device.

Activities during the second half of the past year have largely concentrated on the development of the new and simpler EIS prototype. With a scaled back design, system reliability should be greatly improved. Initial design and layout for a DSP daughtercard and a galvanostat are complete. PCB boards have been built and populated and are now undergoing initial testing and debugging. Code for the DSP core is progressing. Although the new prototype maintains many of the original prototype's design elements, new features are in development or planned. It is hoped to incorporate automatic gain adjustment, utilize time-multiplexing techniques to improve signal power, provide real-time monitors for estimate quality, and develop corrosion state classification strategies, all of which are important to achieving the end goals of a portable and/or in-situ health monitor.

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